

## MOLECULAR INTERPRETATION OF THE X(3872)

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The discovery of the  $X(3872)$  in the  $3\pi J/\psi$  mode is compelling evidence for its molecular nature. A successful prediction of this decay mode and other predictions are reviewed here.

In September of 2003 the Belle Collaboration announced the discovery of a narrow resonance in  $\pi\pi J/\psi$  at 3872 MeV<sup>1</sup>. The proximity of the state to  $D^{0*}D^0$  threshold generated immediate speculation that it is a  $\bar{D}D^*$  molecular state<sup>2,3</sup>. This idea was developed into a predictive model in Ref.<sup>4</sup> by postulating that the short and intermediate range dynamics which drive the structure of meson molecular states are dominated by one pion and quark exchange processes. Thus the interaction Lagrangian was taken to be

$$\mathcal{L} = \frac{1}{2} \int d^3x d^3y \psi^\dagger(y) T^a \psi(y) K(x-y) \quad (1)$$

$$\cdot \psi^\dagger(x) T^a \psi(x) + \quad (2)$$

$$\frac{g}{\sqrt{2}f_\pi} \int d^4x \bar{\psi}(x) \gamma^\mu \gamma_5 \tau^a \psi(x) \quad (3)$$

$$\cdot \partial_\mu \pi^a(x). \quad (4)$$

Here  $f_\pi = 92$  MeV is the pion decay constant,  $\tau$  is an SU(2) flavour generator,  $g$  is a coupling determined by properties of deuteron, and  $K$  is a kernel describing the interaction of constituent quarks. The parameters of the kernel are fixed by meson and baryon spectroscopy. Finally a cut off is introduced to regulate the pion exchange potential and separate short and long range interactions which is also fixed by the deuteron. Thus there are no adjustable parameters when modelling meson molecular states.

One proceeds by projecting the quark-pion level interactions onto the channels of interest. These are  $\bar{D}^0 D^{0*}$  and  $D^+ D^{-*}$  in S-

and D-waves; there are also two nearby hidden charm channels,  $\rho J/\psi$  and  $\omega J/\psi$ . Although these channels are expected to be weak in the  $X(3872)$  they are of central importance because they permit strong decay modes of the  $X$  through the intrinsic widths of the  $\rho$  and  $\omega$ .

The detailed computations of Ref. <sup>4</sup> reveal that only one bound state with  $J^{PC} = 1^{++}$  exists. This state does not have good isospin because its binding energy is of order the mass splitting between the two charge modes of the  $\bar{D}D^*$  channels. This is a generic feature of weakly bound molecular states and provides an important glimpse into any putative molecular state's structure. Since the prediction of these quantum numbers, many additional measurements of  $X(3872)$  properties have been made, and many possible  $J^{PC}$  (*except*  $1^{++}$ ) have been eliminated<sup>5</sup>.

Isospin symmetry breaking allows a weak  $\rho J/\psi$  component of the  $X(3872)$  which, through  $\rho \rightarrow \pi\pi$ , drives the  $\pi\pi J/\psi$  discovery mode of the  $X(3872)$ . Similarly, the  $\omega J/\psi$  component drives the  $3\pi J/\psi$  decay mode. For weak binding the predicted widths of Ref. <sup>4</sup> are 1.3 MeV for  $2\pi J/\psi$  and 0.7 MeV for  $3\pi J/\psi$ , yielding a branching fraction ratio of approximately 56%. Furthermore, the  $3\pi$  Dalitz plot should have events near the edge of phase space, consistent with production via a virtual  $\omega$ . Note that the  $2\pi J/\psi$  prediction implies that the  $2\pi\gamma J/\psi$  partial width is roughly 13 keV.

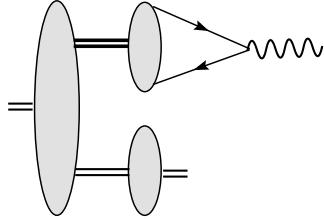


Figure 1. Vector Meson Dominance Diagram.

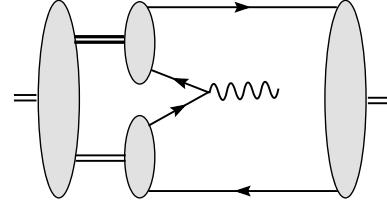


Figure 2. Annihilation Diagram

At ICHEP, the Belle collaboration announced that it had discovered the  $X(3872)$  in the predicted  $3\pi J/\psi$  decay mode<sup>6</sup>. The shape of the  $3\pi$  spectrum is as expected and the measured  $3\pi$  to  $2\pi$  ratio is

$$\frac{\Gamma(X \rightarrow \pi^+ \pi^- \pi^0 J/\psi)}{\Gamma(X \rightarrow \pi^+ \pi^- J/\psi)} = 0.8 \pm 0.3 \pm 0.1 \quad (5)$$

in remarkably good agreement with the prediction.

The only other mention of the  $3\pi J/\psi$  decay mode in the literature comes from Ref. <sup>2</sup> where it is said that this mode is “negligible”. This statement has its roots in an assumed pure  $\bar{D}^0 D^{0*}$  content of the  $X(3872)$ . Thus decay to  $3\pi J/\psi$  is driven by virtual mixing to  $\omega J/\psi$  via the line width of the  $\omega$ . However, the narrow width of the  $\omega$  (8 MeV) versus the large mass splitting between the  $X$  and the  $\omega J/\psi$  channel (7 MeV) implies that this mode should be small. This argument is obviated in the current model by including the  $\omega J/\psi$  channel in the bound state Schrödinger equation. The result may be interpreted as an off-shell  $\omega$  component of the  $X$  which can subsequently decay via its full width.

Once a specific model of the  $X$  has been adopted many predictions are possible. For example, radiative decays may be simply computed in the impulse approximation, as indicated in figures 1 and 2. Predicted rates for  $\gamma\psi'$ ,  $\gamma\psi''$ , and  $\gamma\psi_2$  are very small in contrast to  $c\bar{c}$  expectations of 10-100 keV. The predicted rate for molecular  $X$  to  $\gamma J/\psi$  is 8 keV, at the low end of quark model calculations of 10-140 keV for the  $\chi'_1 c\bar{c}$  state.

Finally, the rate to  $\gamma\gamma$  is expected to be very small (much smaller than typical excited  $\chi$  states) because it either proceeds via a double vector meson dominance diagram or an annihilation diagram where the photons are produced from quarks in different mesons. Both diagrams are suppressed by a wavefunction at the origin which goes like  $|u(0)|^2 \sim \sqrt{\mu_{DD^*} E_B}$  for weakly bound states.

The observation of the  $X(3872)$  in  $2\pi J/\psi$  and  $3\pi J/\psi$  modes implies that this state does not have good G-parity and hence does not have good isospin. Clearly the  $X$  is unusual and it is a leading candidate for a molecular state. Future experimental determinations of its properties will settle the question.

### Acknowledgments

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